Development Of FIAT-Based Thermal Protection System Correlation Models For PICA and Carbon Phenolic

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Introduction and Objective

• As part of the Multi-Mission Earth Entry Vehicle (MMEEV) concept, the Program to Optimize Simulated Trajectories II (POST2) was employed as a tool for solving atmospheric ascent and reentry problems

• Part of POST2's evolution required the development of mass estimating relationships (MERs) to determine the vehicle's required Thermal Protection System (TPS) for safe Earth entry

• The objective of the current work is to develop MERs using FIAT-based correlations with as high an accuracy to FIAT prediction as possible for 840 different trajectories

• Three relations have been developed for these ablative TPS systems: PICA only, Carbon Phenolic atop Advanced Carbon-Carbon, and PICA atop Aluminum 5056 honeycomb.

• The models are accurate to FIAT prediction between 7 to 15% at one standard deviation

FIAT Modeling Constraints

• The maximum temperature at the bottom face of the top material was 250°C

• An adiabatic back face of the material stack up

• A surrounding environment temperature of 21.3°C (for radiation from the spacecraft surface)

• 1D planar geometry

• FIAT v2.6.1

MER Sensitivity Studies

• Sensitivity studies were conducted by plotting required TPS thickness against a variable of interest and looking to see if any correlation existed

• Variables of interest included: peak heat flux, peak surface pressure, heat load, ballistic coefficient, entry velocity, and entry flight path angle

• Of these, heat load and entry flight path angle showed the greatest sensitivity to required TPS thickness and were chosen as the variables to use in a power-law correlation

MER Correlation

Each MER correlations was a power-law fit to the following equation:

$$TH = a\left(HL^b \times EFPA^c\right)$$

TH = required TPS thickness, cm
HL = heat load, J/cm^2
EFPA = entry flight path angle, abs degrees
a, b, c = fit parameters

Modeling Constraints

• No margins were added to the thickness

• For each model developed, about 15% of the trajectories were so mild as to have little or no material recession and therefore were not used as part of the correlation

• A maximum FIAT-predicted TPS thickness is also used, and above this cutoff, the model would diverge rapidly and error would grow substantially

• It should be emphasized that the useful range of the MERs is not the thickness manufacturability range of PICA or Carbon Phelonic, which can be manufactured to a much higher thickness.
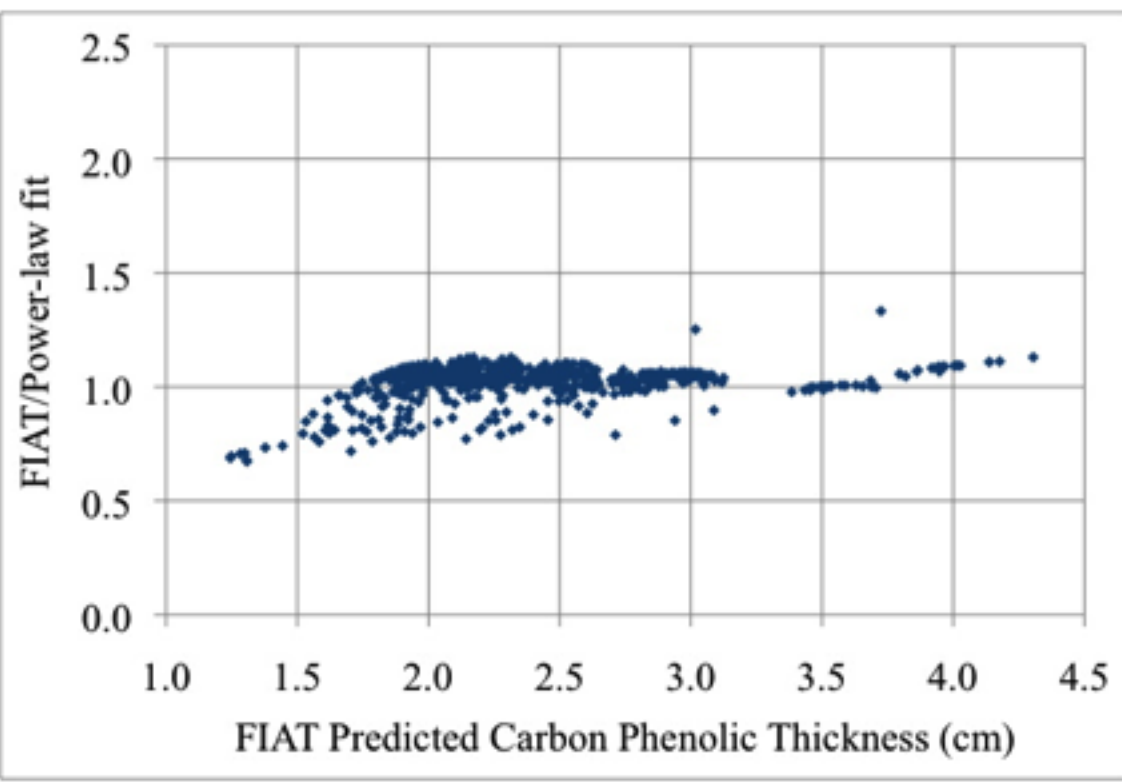
PICA-Only Model

Variable	Values
Velocity [km/s]	10-16
Entry Flight Path Angle [abs. deg.]	5-25
Ballistic Coefficient [kg/m^2]	41.95 – 128.74
Maximum heat flux [W/cm^2]	151 – 3767
Heat Load [J/cm^2]	3855 – 34453
Maximum pressure, atm	0.03 – 3.182
Recession [cm]	0.468 – 3.620
a	1.993062
b	0.13189
c	-0.34152
Accuracy to FIAT at one SD	13.1%
Total number of trajectories considered	840
Trajectories with TPS thickness greater than 4.445 cm	48
Number of FIAT non-convergent trajectories	8
Trajectories with recession less than 0.1778 cm	123
Trajectories used for correlation	661
FIAT TPS thickness range, cm	1.919-4.445
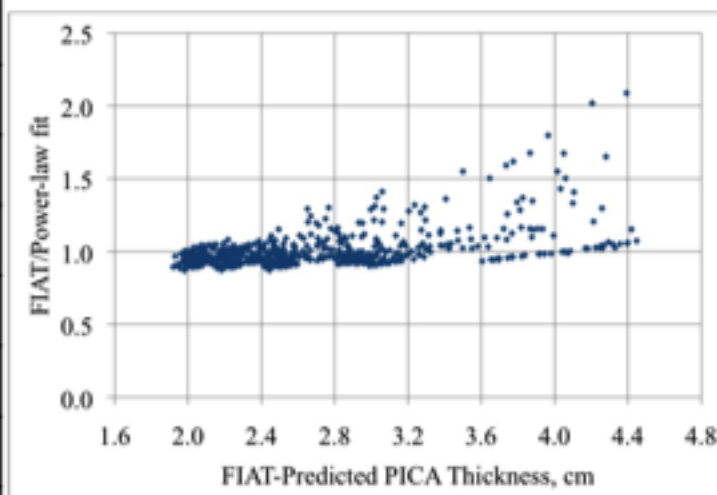
Carbon Phenolic Atop Advanced Carbon-Carbon (ACC)

Material	Thickness, cm
Carbon Phenolic	variable
HT-424 (adhesive)	0.0381
Advanced Carbon-Carbon (ACC) version 6	0.250

Carbon Phenolic Atop ACC, continued

Variable	Values
Velocity [km/s]	10-16
Entry Flight Path Angle [abs. deg.]	5-25
Ballistic Coefficient [kg/m^2]	41.95 – 128.74
Maximum heat flux [W/cm^2]	150 – 3768
Heat Load [J/cm^2]	3855 – 34453
Maximum pressure, atm	0.03 – 3.182
Recession [cm]	0.0458 – 2.713
a	2.366755
b	0.107048
c	-0.374326
Accuracy to FIAT at one SD	7.4%
Total number of trajectories considered	840
Trajectories with TPS thickness greater than 4.304 cm	5
Number of FIAT non-convergent trajectories	8
Trajectories with recession less than 0.0458 cm	123
Trajectories used for correlation	712
FIAT TPS thickness range, cm	1.245-4.304

"Stardust" Stackup

Material	Thickness, cm
PICA	variable
HT-424 (adhesive)	0.1397
Facesheet	0.0508
AL 5056 Honeycomb	1.2700
Facesheet	0.0508
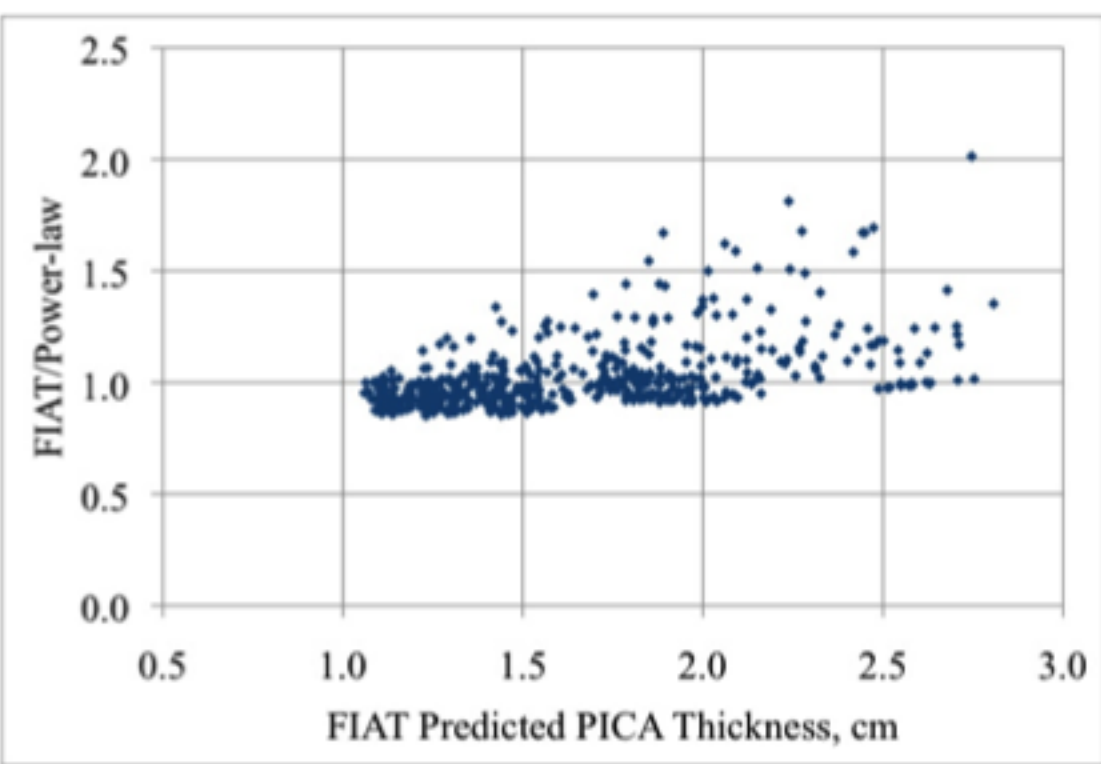
"Stardust" Stackup, continued

Variable	Values
Velocity [km/s]	10-16
Entry Flight Path Angle [abs. deg.]	5-25
Ballistic Coefficient [kg/m^2]	41.95 – 128.74
Maximum heat flux [W/cm^2]	157 – 3767
Heat Load [J/cm^2]	3855 – 29205
Maximum pressure, atm	0.05 – 3.182
Recession [cm]	0.470 – 2.488
a	0.757031
b	0.207252
c	-0.425836
Accuracy to FIAT at one SD	14.9%
Total number of trajectories considered	840
Trajectories with TPS thickness greater than 2.807 cm	99
Number of FIAT non-convergent trajectories	7
Trajectories with recession less than 0.1721 cm	123
Trajectories used for correlation	611
FIAT TPS thickness range, cm	1.060-2.807

PICA Arcjet Testing Database

These correlations include a peak heat flux of over 3700 W/cm^2 as part of its applicability range. PICA has never been tested under such high heating, and it is unlikely to be able to withstand such conditions, so caution must be used when considering a trajectory for use with a PICA MER.
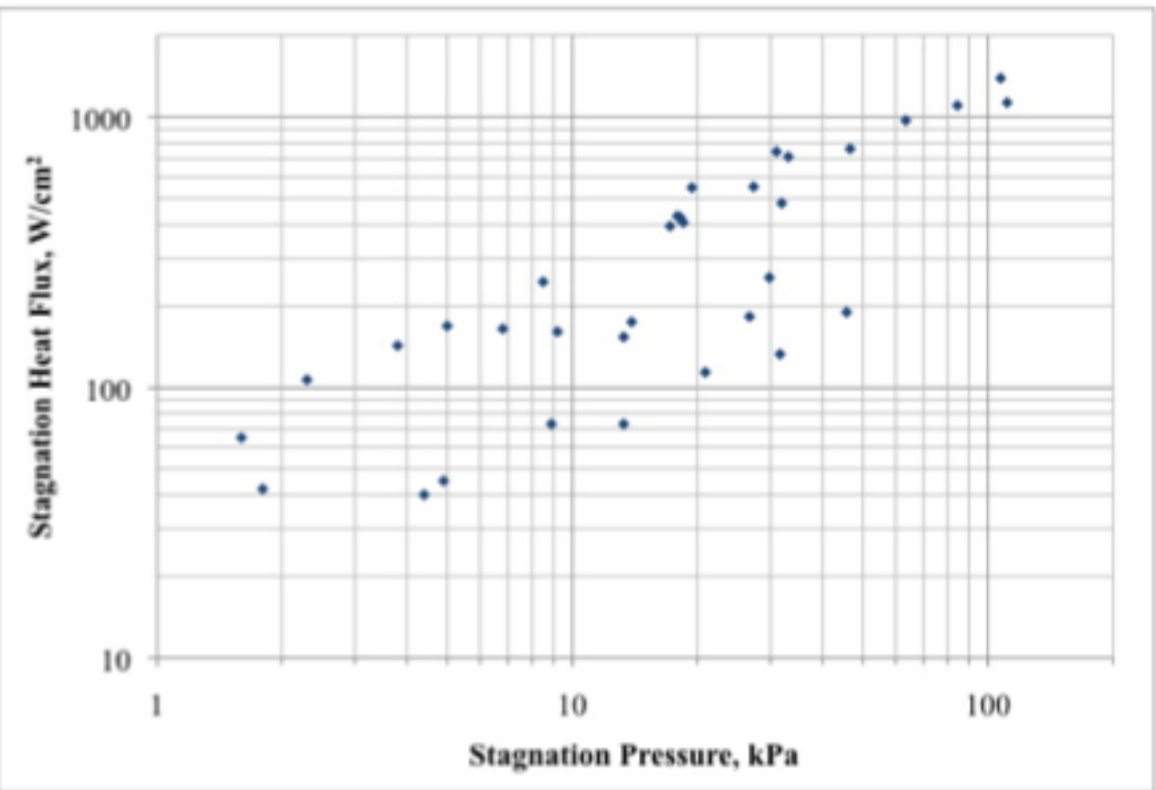
Stagnation tests (2007-2010) of PICA in which no spallation or failure was observed

Results and Future Work

• MERs have been developed for PICA and Carbon Phenolic based on entry flight path angle and heat load

• PICA MERs are accurate to within 15%, and Carbon Phenolic MERs to within 8% (both at one standard deviation) of FIAT prediction

• The MERs are only valid for a well-defined predicted thickness range

• The trajectory space to develop the MERs considers flight conditions to which PICA has not been tested, so care must be used when applying the MER for a given flight condition

• PICA and Carbon Phenolic can be manufactured to much a much greater thickness than the MER applicability range

• Future work would be in the development of MERs for additional material stackups and to update existing MERS with an expanded flight trajectory space